A Framework for Collaborative Design in Engineering Education

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The Collaborative Design Environment (CoDE) is a dedicated collaborative design facility aimed at enhancing design team communication by supporting collocated system and discipline experts with analysis tools, design applications and various technologies. A generalized model of collaborative design offering flexibility and concurrently addressing the environment and the process as complementary counterparts is proposed. A detailed process was constructed by strategically aligning pertinent models of collaborative design from a variety of fields. The process clearly describes how technological affordances in the CoDE can be used to address the collaborative design challenges and leverage its advantages. This process was successfully implemented by a team of undergraduate aerospace engineering students participating in the 2006 AIAA aircraft design competition. The process, the environment and the generalized model serving as a flexible reference frame constitute a framework for collaborative design.

I. Introduction

THE Collaborative Design Environment (CoDE) at the Aerospace Systems Design Laboratory (ASDL) of the Georgia Institute of Technology is a dedicated collaborative design facility aimed at enhancing design team communication in a 'war room' environment, supporting collocated system and discipline experts with analysis tools, design applications and various technologies. Other similar facilities include the Project Design Center at the Jet Propulsion Laboratory, the Concept Design Center at the Aerospace Corporation, and the Concurrent Design Facility at the European Space Agency. The CoDE is tailored for rapid turn-around time design projects of complex systems requiring a collaborative and interactive approach to perform requirements analysis, varying-fidelity modeling and simulation, feasibility and viability assessments, and technology studies in the decision space among other primary design tasks. The primary goal of the CoDE is to provide a technology-mediated physical setting for the collocation of all stakeholders so as to enhance design process and improve the overall quality of the end product. [1]

Osburg and Mavris[1] indicate that the design of the CoDE was based on lessons learned from the operation of the aforementioned design facilities and from experience facilitating and conducting team-centered multidisciplinary design. None the less, little information is provided by this reference on the nature of a general collaborative engineering design model or on the specific exercises that the CoDE was designed to support. Though communication is clearly stated as a key supported function it is treated at a high level of abstraction, other functions such as modeling and simulation or feasibility assessments are identified but only in a generic manner. A specific process enabled by the technological resources in the CoDE that leverages collaborative engineering design at a tactical and strategic level is lacking. Furthermore, a majority of existing generalized models for collaborative design are found to devote almost exclusive attention to either process or environment, and fail to provide a flexible formulation that addresses both concurrently. Thus a relevant generalized model for collaborative design is missing as well.

Benford et al.[2] recognize that this is a recurring problem for different design environment formulations. Collaborative environments are viewed as interaction-rich arenas designed for the accomplishment of collaborative work. While recognizing the availability of technology and increasing technological affordances, it is noted that the challenge lies on how these environments are used: "Collaborative environments increasingly offer themselves as

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one of a range of potential technologies to support the work of groups. However, what is less clear is how these systems should be used to support the work of groups and how we should design environments to support work in practice.”[2]

This paper documents the formulation of a collaborative design framework comprised of a generalized model and a clearly defined process technologically enabled by the existing supporting environment (CoDE). First, a brief overview of the CoDE and its supporting assets is presented in Section II. Section III provides a relevant definition of engineering design and addresses some of the main issues of collaboration and team-oriented efforts. Based on these issues a general model for collaborative design that highlights key concepts and challenges is proposed in Section IV. A series of specific models pertaining to a wide spectrum of fields including engineering education, cognitive engineering, software design, and psychology are reviewed in Section V. These models are aligned into a clear process with an adequate level of tactical detail. The process is presented as fully implemented in Section VI. In accordance with the CoDE’s purpose as an educational resource as well as a research-oriented one the implementation reported is that of a team of aerospace engineering students participating in the 2006 AIAA undergraduate aircraft design competition. Section VII presents conclusions and final remarks.

II. Overview of the CoDE

The modular floor-plan of the CoDE shown in Fig. 1 depicts a main working area that centers around the main team work table, and two smaller and identical break-out areas that can be isolated by curtains. The main table is equipped with a computer, a PC projector and a Sympodium touch screen. The Sympodium screen looks very much like a flat panel computer screen and lies inclined on the main table. This screen however has the features of the SMART Board as it allows the user to control the computer with the touch pen. The image of the computer feeding into the Sympodium is projected onto the main stage projection screen.[3] The main stage also hosts a whiteboard and a Front-Projection SMART ™ board on either side. The SMART board uses a standard projector for PC and offers interactive resources which include the SMART Markers and eraser capabilities, writing typing and drawing, controlling the computer by touching the SMART Board screen, adding content into notebook software, capturing and saving data, and presentation aids among others.[4]

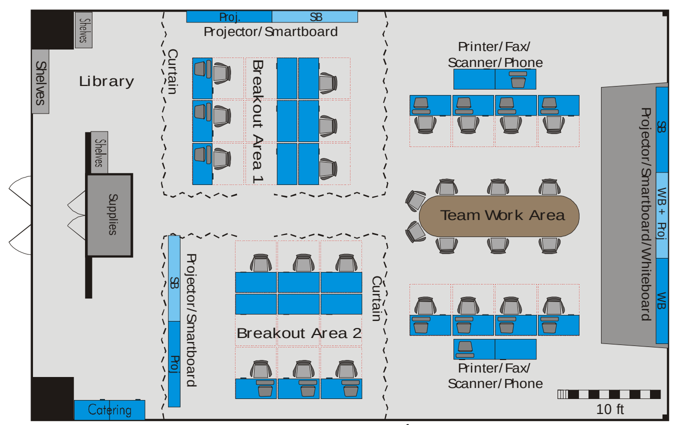

Figure 1. Floor plan of the CoDE. [1]

Peripheral computers are located on the side work stations and can be remotely accessed from any other station via remote desktop software. Communication and supporting assets include wireless conferencing phone with remote microphones, digital camera systems, and printer/fax/scanner/copier multifunction units.

III. Engineering Design and Collaboration

To identify the motivation behind collaboration in engineering design it is important to establish a relevant definition that highlights its challenges. Nahm and Ishikawa define engineering design as a “transformation process from a set of functional specifications and requirements into a complete description of a physical product or system which meets those specifications.”[5] Tormey et. al. define it as a process where a team makes decisions to solve specific problems based on implicit knowledge and uses available methods to transform information from customer requirements into detailed design behavior.[6] Based on these and other widely accepted definitions the following are identified as key features of engineering design:

- Engineering design is a decision-making activity
- Engineering design is a problem-solving activity
- Engineering design is a cognitive activity, that is, relies on the construction of knowledge
- Engineering design involves transformation of information
- Engineering design involves considerations of the entire life-cycle of the product
- Engineering design is inherently multidisciplinary

With the pace and scope of design problems continuingly growing it becomes increasingly difficult, if not impossible, for a single individual to assimilate all necessary knowledge and cover all possible disciplines. Design problem complexity and sheer size thus forces heterogeneous groups to work together over long periods of time.[7]

Collaborative design focuses on the implementation of the design process by said groups of participants attempting to reach a common goal by supporting, via processes and environments, the collective execution of design tasks such as constructing a knowledge base, making decisions, and transforming information. The main premise of this approach is that collaborative design is not only desirable but necessary as it enables the efficient execution of the design process, significantly reducing the design cycle time while increasing its quality and that of the end product.

The immediate issue with collaborative design is that decision-making, problem solving, and knowledge building are interdependent and must now take place in a team environment. Work on decision-making highlights the importance of context in the decisions,[8,9] capturing the rationale behind them and requiring a situational assessment prior to the decision event. In team decision making a set of common goals contrasts with the often opposing agendas of the different members and their changing understanding of the problem.[10] Thus a common knowledge base where the context is defined uniformly across the entire team is critical.

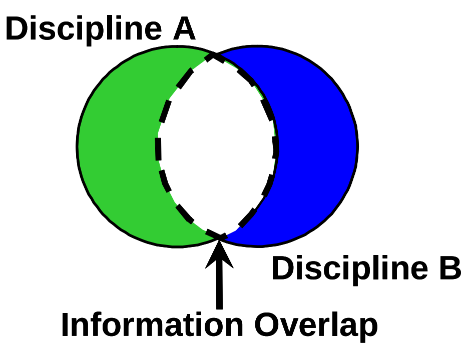

Figure 2. Synergistic organization of information across disciplines in a team effort.

Work on team problem solving also highlights the importance of a meaningful context, shared knowledge and information distribution. An important contributing factor in team problem solving performance is the formulation of shared mental models. Sperling explains that improved outcomes in team problem solving not only depends on the overlap of knowledge among members but also on the synergistic organization of knowledge among members. This idea suggests that "in certain instances individual members of a team do not require complete overlap of all information within a problem space in order to possess a congruent and accurate team mental model of a defined problem."[11] In turn there will be a portion of the individual knowledge or information base that is not shared explicitly with the rest of the team, particularly in the instance of subject matter experts. The concept is visually represented in Fig. 2. This is certainly the case in fields such as aerospace engineering where, for example, aerodynamics and structures experts need share only some relevant information with each other in the design of a wing, but do not need to share in-depth discipline specific theories or reference data.

IV. Generalized Model for Collaborative Design

The proposed general model for a collaborative design process, illustrated in Fig. 3, depicts a team of designers sharing common goals but conflicting agendas. The team members require communication channels to propose ideas and negotiate solutions. The problem-solving and decision-making processes that are involved in the argumentation and negotiation of solutions take place within a meaningful context. This context in turn is defined by the shared knowledge base constructed by team learning and information sharing.

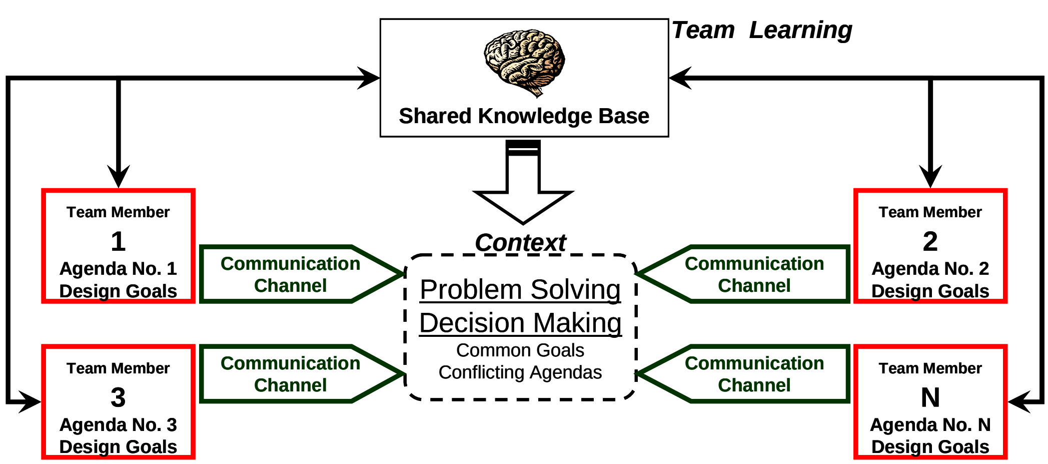

Figure 3. Generalized Model for Collaborative Design.

V. Models of Collaborative Design

Research on collaborative design consistently identifies communication and knowledge sharing as key enablers. It follows that efforts in collaborative design theory and technological mediation focus on these issues and provide resources to enhance them and adequately support team decision-making and problem-solving. A large number of research efforts in this subject matter were reviewed. However only those most relevant to the objective and scope of this study are presented.

Work on collaborative design includes that of Arias et. al. who propose a model of action and reflection spaces. In this formulation designers modify the characteristics of a product in an action space and access tacit knowledge from all the stakeholders, otherwise unavailable to the team, via a reflection space. By making this tacit knowledge explicit designers are better informed and make more strategic decisions.[7] To illustrate this concept think once again of the example of different aerospace discipline experts performing a typical aircraft design task. Suppose that for the conceptual design of a supersonic business jet the aerodynamicist proposes a long and swept back T-tail. However upon inspection the structures expert voices his concern with flutter issues and the program manager suggests that such exaggerated features are a risky proposition to top management of the aircraft manufacturer. How can these assertions be made by experts if no aeroelastic analysis has been performed and communication with manufacturing decision-makers has not taken place in such early phases of design? The tacit knowledge of both structures experts and program manager has been accessed (reflection space) and may be further explored upon inquiry at an explicit level. The aerodynamicist can then adjust his design accordingly (action space).

Geisler and Rogers[12] address information sharing, knowledge building and effective communication through the use of public and private spaces. In this model designers work in their particular field of expertise within a private space and use technology mediated environments and structured processes to bring information relevant to the entire team within a public space. This model aligned with Sperling's ideas of shared and complementary mental models presented in Section III. Their recommendations address the adequate interweaving of these two spaces by means of the following process:

- Sharing: introduce and review the results of private work.
- Proposing: Formulate proposals and counterproposals about how to proceed with the work
- Discussing: Explore the implications of proposals, pointing out issues and arguments for and against adopting them
- Ratifying: Collectively ratify or adopt a proposal
- Updating: Update current understanding of work given ratified proposals
- Disseminating: Disseminate back to private individuals the results of the conversation in the form of a revised current understanding of the work

Lehto and Marttiin propose a model where shared cognition is enabled by social action. The model describes a process where tacit knowledge is made explicit by each member (externalization), shared explicitly between members (combination), and then encoded again by each member (internalization). The salient feature of the model consists of a socialization step by which critical knowledge is transferred between members in a purely tacit form and without the need to be externalized. This proposition highlights face-to-face interaction as highly desirable as it allows the largest amount of information exchange and shared knowledge building.[13]

Fischer and Grudin[14] concurrently address the elements of context and communication in collaborative design. This reference indicates that communication may take place synchronously (e.g. face-to-face, phone call, videoconference) or asynchronously (e.g. documentation, milestone reports, email). Documentation of context is a means of asynchronous communication and is paramount for projects spanning large time periods such as those typical of the aerospace industry where designers may join or leave the team throughout the duration of the project (e.g. Apollo program, ca. 1963 – 1972). In their approach technological resources are used to capture the rationale of design decisions as shaped by the context of that point in time, access them easily at any future instance, and embed this information explicitly as part of the design product itself.

VI. Formulation of a Collaborative Design Process for the CoDE

Before presenting the details of the collaborative design process it is important for the reader to remember that this process results from the alignment of the relevant models reviewed in the previous section and that it uses the generalized model introduced in section III as a frame of reference. As such the process addresses the key aspects and challenges of collaborative engineering design, namely communication, group cognition (learning, knowledge building, context building), team problem solving and team decision making.

The team competing in the 2006 AIAA undergraduate aircraft design competition representing the Georgia Institute of Technology began their efforts by establishing an organizational structure with a project manager, chief engineer and lead researcher for all major disciplines. A statement of work was formulated by the entire team establishing the general purpose and objective of their efforts. This represents the initial steps in the construction of a shared knowledge base and the collective definition of a relevant context for their project

Throughout the entire span of the design project the students performed extensive research via literature review of technical papers, review of online technical websites, short courses, periodicals and books. In the early stages however most of the literature search constituted background research which was to be shared and understood by the entire team. The background not only served as another basic building block in the creation of context but more importantly forced the even dissemination of information and the collective creation of shared knowledge that would later guide efforts at the discipline-specific level. The background thus becomes the first part of the information and knowledge overlap explained by Sperling[12]. Beyond this point team members continued their research and began sizing & synthesis efforts shifting focus to their specific discipline.

The effective construction of shared mental models required that some of this information, procured by individual subject matter leads, be shared with the rest of the team. This constitutes information management by each individual in the sense that each must allocate it in either the shared region of overlap across disciplines (see Fig. 2) or in the discipline specific region. More importantly however is the fact that this shared information has to be effectively disseminated to all other team members for the collaborative building of team knowledge.

To this effect the model of public and private spaces (Ref. 12, presented in Section V) is invoked, particularly the process of interweaving the two spaces (sharing, proposing, discussing, ratifying, updating and disseminating) in a technology enabling environment. This structured exercise of negotiation and dissemination of commonly agreed issues was repeatedly used with much success and was enabled by the adequate use of the main table and the main stage as the public space for the team. A snapshot and explanatory diagram of this exercise in the main table is shown in Fig. 4.

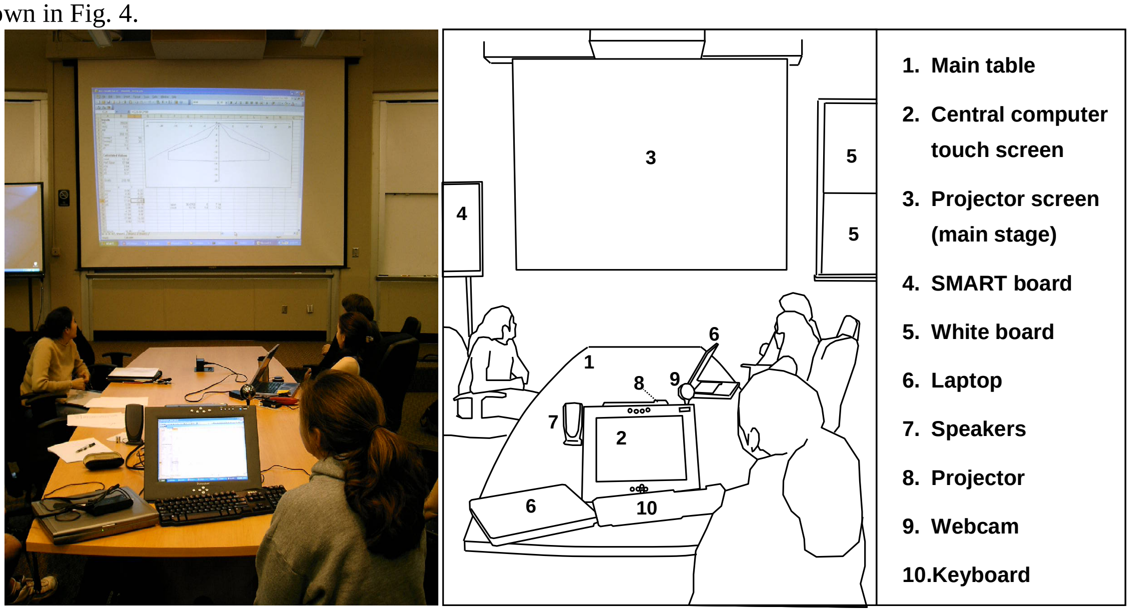

Figure 4. Main table and projection screen serving as public space.

Note that team members are all sitting around the table, an important feature of this exercise that highlights the value of face to face interaction as noted by the model of social action in Ref. 13. The main computer is projected both on the main stage screen and on the Sympodium touch screen. This facilitates the use of tools and applications for the team member presenting information, allowing him/her to “drive” the process with ease while other members have a very open view of the information presented.

When the discussion and ratification steps took place a negotiation occurred between members with conflicting agendas. This situation often required that other members present their findings. In traditional settings there is a time lag associated with passing from one member to another and accessing relevant files, loading programs, etc. These time-consuming interruptions during negotiation were effectively minimized by using laptop computers with which, in many cases, team members performed the bulk of their work in the first place (see Fig. 4). Connection with the projector was switched effortlessly from the main table computer to any laptop where the relevant information, tools or applications were readily available.

The SMART board on the main stage was often used to present complementary information to that on the main screen. It also offered an alternative for team members presenting information during discussion / negotiation without having to switch computers and allowed for the concurrent display of independent computers on the same main stage. The SMART board in this setting, shown with an explanatory diagram in Fig. 5, used the second projector which was connected to one of the peripheral work stations that could map any of the other work stations in the CoDE.

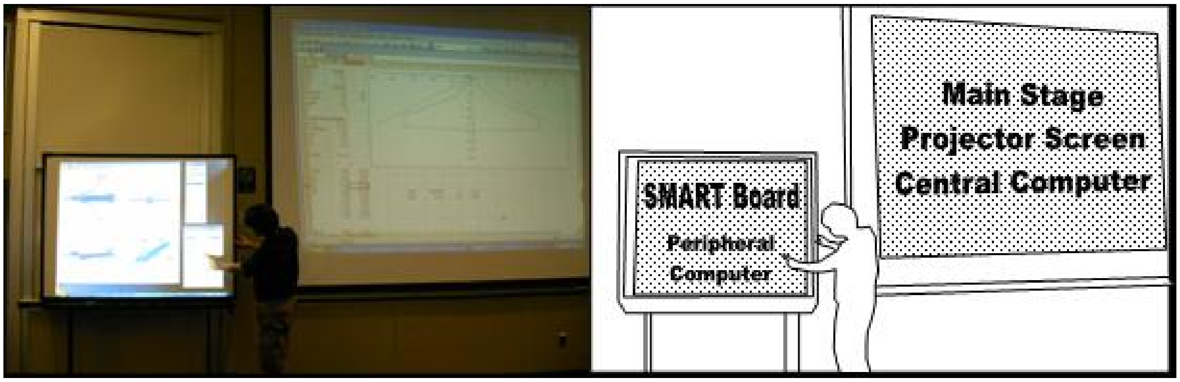

Figure 5. SMART board in main stage used as complement in public space.

This process used the CoDE's main area and main stage to effectively interweave public and private spaces leveraging communication and team cognition for the negotiation of shared mental models and the construction of a shared knowledge base. Execution of this process is illustrated with a key example: Early in the project the team performed a quality function deployment exercise where a house of quality[15] was used to map customer requirements specified in the RFP provided by the AIAA to engineering characteristics of the vehicle under consideration. Defining these characteristics, ranking them and mapping them required extensive argumentation by all team members. Keeping the house of quality matrix projected and having readily available electronic sources collected by each independent member greatly leveraged the performance of the team thus reducing the time for the activity and increasing quality of the resulting document.

After the bulk of the background research had been performed the team's resource management strategy gradually shifted from non-differentiated team effort to a distributed allocation of tasks according to disciplines. At this point the subject matter leads were able to take significant level of ownership of their parts in the overall scheme of the project. Design trade-off analyses as well as sizing and synthesis iterations began at this point and the different leads began to make use of tools analyses varying in levels of fidelity.

This work dynamic was conducive to a process where leads worked by themselves but communicated findings and developments to the rest of the team. Although each student was performing work individually questions and concerns that directly affected or involved other disciplines often surfaced.

The discipline specific tools were available in all the peripheral computers of the workstations about the main table. These workstations were effectively used as private spaces where members responsible for different disciplines ran said tools. The problem solving and decision-making involved in the negotiation of a solution, as enabled by the interweaving of the private spaces (workstations) and the public space (main table and projector) was effectively achieved by two means. The first and most obvious one was having the entire team in the same room. Once again the value of social interaction as a channel to access tacit knowledge directly is leveraged.

The second, remote desktop software, allowed for any of the peripheral workstations to be mapped on any other computer and/or projected onto the main screen for the entire team to observe. The access of individual private spaces on the public space was particularly helpful whenever decisions had to be made and the individual team member was not clear on how it would affect the work on other disciplines. A composite picture of the CoDE, shown in Fig. 6, depicts the main area in use and the peripheral workstations being used as private spaces.

Team structure not only reflected the different disciplines of the problem (aerodynamics, structures, controls, performance, etc) but also reflected, beyond the initial stages of the project, the distribution of modeling and simulation responsibilities according to discipline (FEA, performance analyses, 3-D CAD, vortex lattice package, etc). It has been stated that the entire team is affected and involved in a design decision that pertains primarily to one discipline. However, with the use of analysis tools problems specific to analysis packages, modeling tools and integration between them arose. This type of problem often involved only a handful of team members and contrasted with design decision and problem solving negotiation.

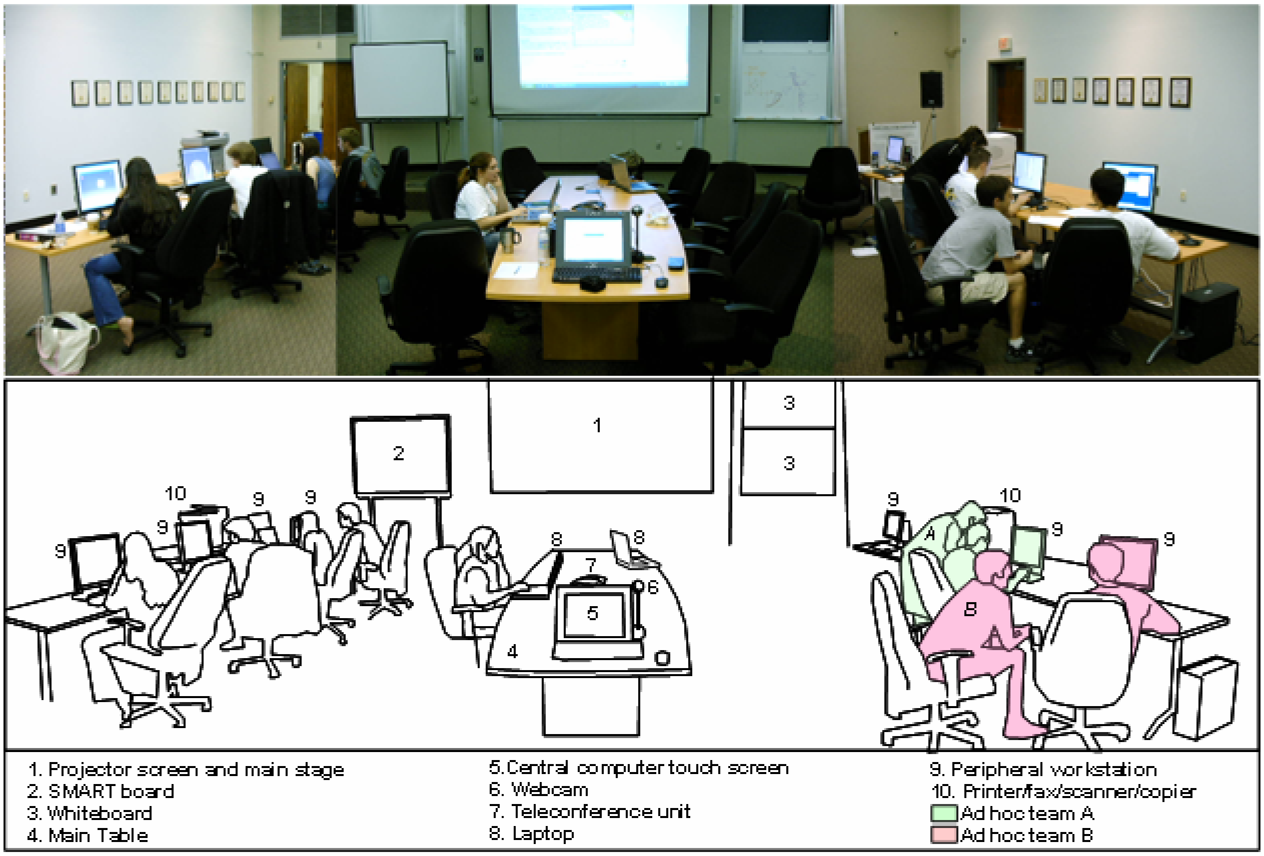

Figure 6. Main area of the CoDE - main table and peripheral work stations.

The members took full advantage of the collocation of the entire team in the CoDE and used it to create ad-hoc teams that addressed the aforementioned modeling tool challenges. Two ad-hoc teams have been identified and labeled in Fig. 6. While the physical presence of the entire team on the same location may seem like a trivial enabler for collaboration, it was observed that it allowed for an effective solution to specific problems involving only a few discipline leads, not the entire team. Attempting to address these issues with the entire team would have clearly represented a wasteful allocation of resources.

Another means of enabling communication and enriching the common knowledge base was by accessing tacit knowledge within each of the discipline leads. This was done using the SMART board on the main stage as action and reflection spaces. It was found that making use of these resources was particularly helpful for design decisions and problems involving configuration selection, allocation of components in the internal layout, and in general issues involving geometric representations of the vehicle. As a primary example Fig. 7 shows the student responsible for the generation of the 3-D CAD model (left) actively using the board to modify the design object (action space). The student responsible for stability and control (right) is providing feedback on the location of a main internal fuel tank and other major components that would affect the position of the center of gravity. Similarly the student in charge of aerodynamics (not shown in picture) is providing feedback on implications of wing location and inlet placement. Although the different disciplines are represented in this dialogue the information transfer is not explicitly instantiated but is instead tacit knowledge

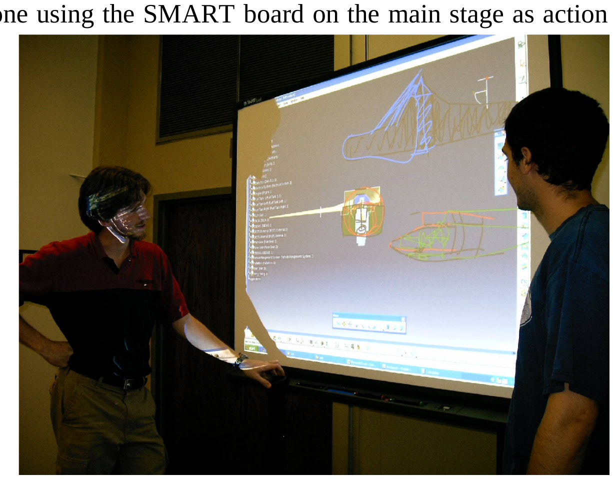

Figure 7. SMART board and main stage used as action and reflection spaces.

embedded in the feedback that the CAD student uses to continue building the model and be informed for future decisions.

As an exercise this same task was performed using a normal computer screen with keyboard and mouse. Although both team members could implement changes (action space), accessing knowledge or effective feedback from one another was either non-intuitive or not possible at all. Students indicated that having a window open for the CAD model and one for the stability calculations required additional effort, and that working on a CAD model with half a computer screen (the other half devoted to the window for the stability calculations spreadsheet) was somewhat difficult. On the other hand they indicated that performing the task on the SMART board greatly improved the quality of the process while reducing the level of difficulty in communicating. This was due to four main features: 1) the size of the work space which was well suited for CAD modeling, visualization-intensive applications, and small group exercises, 2) the ability to modify the design on that workspace with touch, directly avoiding an interface with a screen, keyboard and mouse, 3) the affordances provided by the virtual markers and other visual aides that allow for markup and visual tools that do not affect the actual CAD software while making the exercise more engaging for all participants, and 4) the ability to capture and save the entire screen image with virtual marker sketches and author comments. The photograph shown in Fig. 7 depicts the CAD model as well as additional virtual sketches done on top by participating team members.

The management of information and documentation of context was implemented through SubVersion, a revision control system that allows collaboration by keeping a history of changes made to the different files over time.[16] This resource allowed the team to mix and match versions of files with ease keeping every member instantly current. Through the basic commands of the software different members of the team were able to work on the same file at the same time, allowing for real time co-development of analysis input files, in-house tools and final report. The changes are authored, dated and commented to further leverage the documentation of context as rationale behind certain decisions. This proved to be a valuable feature particularly for the constant modification of input files used in the different analysis tools. This process was effectively embedded into the final design product while keeping a record of the evolution of the vehicle through the different design decisions and problems addressed. Adequate use of emails to the team's email list also contributed to the dissemination of information, accounting for effective asynchronous communication that kept the entire team informed on administrative or technical issues.

VII. Conclusions and Final Remarks

Published work addressing the CoDE provides a sufficient description of the environment and the technological affordances that the various assets offer. None the less, two important elements were found to be lacking: 1) a process with appropriate tactical detail, and 2) a generalized model for collaborative design offering flexibility while addressing the environment and the process concurrently. Answering to this gap a generalized model was formulated highlighting the key concepts and challenges of collaborative design. The model identifies communication and group cognition, problem-solving and decision-making as interdependent and critical elements.

Using the generalized model as a starting point and frame of reference a detailed process was constructed by strategically aligning pertinent models of collaborative design from a variety of fields. The process clearly describes how technological affordances in the CoDE can be used to address the collaborative design challenges and leverage its advantages. This process was successfully implemented by a team of undergraduate aerospace engineering students participating in the 2006 AIAA aircraft design competition.

The process described in this paper serves as a complementary counterpart for the CoDE and along with the generalized model constitutes the formulation of a collaborative design framework. The process offers an adequate level of specificity and detail, and exploits in full the capabilities of mediating technology in the environment.

It is important to note that the process is not specific to the CoDE and that the generalized model is flexible enough to explain collaborative design in varying degrees of complexity and scope. Other environments with similar technology and assets can be leveraged to produce high quality results if those who make use of said environments adequately adopt the process and execute their implementation of the framework with the generalized model as a reference.

Acknowledgments

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